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DYNAMIC ASSESSMENT OF CABLE-STAYED BRIDGES IN EGYPT

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ABSTRACT

Bridges are indispensable components of the infrastructure of modern society, and their assessment via techniques of structural dynamics is assuming greater importance. Dynamic behaviors of Suez-Canal and Aswan cable-stayed bridges were investigated through three-dimensional finite-element models. Seismic response analyses have been conducted from the deformed equilibrium configurations due to bridges own-weight. TAFT earthquake record was used in the analysis. The earthquake record was input in the bridges longitudinal, lateral, and vertical directions simultaneously. Results show that the bridge statical system has dominant influence on the bridge vibrations and there is a strong coupling in the three orthogonal directions within most modes of vibrations. Results include dynamic characteristics, time-history and frequency –domain responses.

KEYWORDS: Cabel-Stayed Bridges, Seismic Response

INTRODUCTION

Since cables instead of interval piers support cable-stayed bridges, they are much more flexible than conventional continuous bridges, especially for long-span bridges, Bruno and Leonardi (1). In view of the characteristics of the structural supporting conditions, bridge decks and pylons are subjected to strong axial forces (compression forces) arising from cable reactions, Matsumoto and et al. (2) and Brownjohn, and Xia (3). The axial forces acting on the bridge deck and pylons will cause geometric nonlinearity. In addition to the axial forces, some of the most important factors on the analysis of cable-stayed bridges are the cable nonlinearity due to its own sag, the interaction between the cables and the bridge deck, and the interaction between the cables and the pylons. A common approach to account for the sagging of inclined cables is to consider an equivalent straight modulus of elasticity, Gimsing (4).

$$E_{eq} = \frac{E}{1+((L_o\gamma)^2/12\sigma^3)E} \tag{1}$$

Where, E_{eq}= equivalent elastic modulus of inclined cables, E= tangent modulus of elasticity for the cable,

Lo= horizontal projected length of the cable, γ= weight per unit volume of the cable, and σ= cable tensile stress. The above equation gives the instantaneous tangential value of the equivalent elastic modulus that the cable tensile stress reaches. Cable arrangement can be in a single plane or double plane systems.

In this paper, to study the dynamic response characteristics of the Suez-Canal and Aswan Bridges under seismic loads, a seismic response analyses were carried out for an exact three-dimensional models of the Bridges.

TAFT earthquake record was used in the analyses. The results include determination of the dynamic characteristics of the bridges (different mode shapes and associated periods of vibration), time-history and frequency –domain responses.

Cable-Stayed Bridges in Egypt

The Suez-Canal Bridge: The bridge has a total length of 730 m and 21 m in width. The central main span crossing the Suez Canal is 404 m, and two side spans of 163 m each. Considered as one of the highest cable-stayed bridge in the world (70 m above the Suez Canal). A total of 132 cables are used to support the steel girder. Outlines of the main bridge elements are as follows: (1) the steel Girder has a box-type cross-section with maximum depth at the center of 2.6 m, 21 m in width, 730 m in length, and a total weight of 7400 tons, (2) two reinforced concrete pylons where, Each pylon is rested on 48 deep piles (L=32 m). The pylon has an H-shape column with a total height of 154 m and a crossing beam at a level of 124 m., (3) the stay cables are parallel galvanized wire strands (New-PWS). Cables configuration is a semi-fan type with total of 4X16 cables in each plane (Cables are in double planes). Cables are distributed as equidistant every 10 m for side spans and 12 m at main span., (4) high damping rubber bearings (HRB) were used as seismic isolators (supports) for the steel girder, with allowable movable length (seismic) = ± 450 mm. To limit the horizontal movements, lateral rubber bearings were installed between the bridge deck and the tower with a gap of 10 mm. The bridge statical system is composed of two separated structural units; 1) pylon rested on piles, 2) bridge deck with all supports are rubber bearing except for the end supports are roller type.

The Aswan Bridge: It is located near Aswan city southern of Egypt. It has a total length of 500 m. and 24.3 in width. The central span crossing the Nile River is 250 m. and two side spans of 125 m. each. The bridge consists of a continuous concrete deck, two hollow box-shaped towers, and one-plane semi-fan type of cables. Outlines of the main bridge elements are as follows:

(1) The bridge deck is a prestressed segmental concrete deck of a single cell trapezoidal box-girder with two inclined webs, 42 cm in thickness, (2) a single vertical plane of 56 cables along the middle longitudinal axis of the superstructure is located in a single vertical strip. The stays are composed of 73 to 109 H15 strands surrounded by an HDPE tube (high-density polyethylene sheath). Each strand is 15.7 mm in diameter containing 7 wires. The breaking load per wire is 265 KN., (3) there are two towers (west and east) and six piers. The tower is a prestressed concrete structure, fixed to the deck, has a box girder shape with outer dimension 3mX6m (1mX3m inner dimension). The tower height is 55m from the deck level. The stays are anchored to the tower on a vertical range of about 30m., (4) two lines, 8/ line, of elastomeric bearings are placed on top of each pier shaft (7& 8) to support the bridge deck. The bearing size is 1000X1000X160 mm. Two PTFE, 600X600X60 mm, bearings are placed on piers 5,6,9,and10 to permit longitudinal movements and to limit horizontal deflections. Generally, in the case of single-box main-bridge system, the towers are fixed to the superstructure (the deck) which is the case under study. Towers and the bridge deck are considered to be one structural unit, since towers are fixed to the deck. Therefore, the bridge statical system is composed of two separate structural units; 1) towers and deck, 2) piers. The first unit is rested on rubber bearings which are fixed to the pier.

A schematic representation of both bridges are shown in Figure 1.

FINITE ELEMENT MODEL

The bridges are discretized as three-dimensional-finite-element models, which include three types of elements: frame, shell, and cable. First, bridge decks have been modeled as shell elements. Next, towers and pylons have been modeled as three-dimensional frame elements. Each node of both shell and frame elements incorporates six degrees of freedom, i.e., translation in the X, Y, and Z directions as well as rotation about all directions. Last, the stayed cables have been modeled as tension-only elements. Therefore, if the cable element is subjected to compressive forces, the cable stiffness will be taken as zero. In order to effectively model the structure, material properties are assumed as follows.

For concrete, the modulus of elasticity E is 30 Gpa; Poisson's ratio υ is 0.25; and the mass density is 23.2 KN/m^3. For steel, the modulus of elasticity E is 200 Gpa; Poisson's ratio υ is 0.3; and the mass density is 78.6 KN/m^3. The material behavior is linearly elastic and the modulus of elasticity E in tension and compression are equal. The damping ratio was assumed constant and equal to 3%, which is the common percentage of damping in this class of bridges, Lichu et al. (5). The vertical and horizontal stiffness of the bearings are calculated according to the following formulas:

$$S = \frac{L}{4e} \ , \ E_a \approx 6GkS^2 \ , \ K_V = \frac{AE_a}{L_r} \ , \ K_H = \frac{AG}{L_r} \tag{2}$$

Where, S = Shape factor, L_r = bearing's length, e = rubber layer thickness, E_a = Apparent modulus of elasticity corrected to account for rubber compressibility, G = shear modulus, k= rubber compression modulus, K_V = bearing's vertical stiffness, K_H = bearing's horizontal stiffness, and A= rubber layers cross sectional area. The damping coefficient ratio for bearing was taken 10%, Gimsing (4). The calculated bearing's stiffness equation (2) are substituted for the links stiffness. A numerical analysis is carried out based on the tangent stiffness method and modal superposition. For Suez-Canal Bridge; two horizontal rigid links (gap elements with 10-mm gap opening) were used in this study to simulate the action of the lateral restraining blocks. The rubber bearings were simulated by linear link elements. For Aswan Bridge; the connection between the deck and piers 7 and 8 are modeled by rigid link in the vertical and horizontal directions to allow the deck to move freely in the longitudinal direction and rotate freely about the transverse axes of the deck. The connections between the deck and piers 5, 6, 9 and 10 are modeled by swing rigid links to restraint the relative movement between the deck and the piers in the vertical direction.

DYNAMIC ANALYSIS

In recent investigation, Lich et al. (5), concerning the dynamic analysis of cable-stayed bridges, it was assumed that only one earthquake component shocks the bridge at the supporting points. Therefore, there is an urgent need for more comprehensive investigations of seismic analysis of cable-stayed bridges taking into account a three-directional ground shaking excitations simultaneously. To evaluate the different dynamic characteristics of the bridges, three components of the Taft record were considered. Analyzes were carried out in both time and frequency domains. It should be noted that all analyzes started from the deformed equilibrium configuration due to bridges own-weight. Since there are a tremendous amount of results, only key response results will be considered.

Equation of Motion

The dynamic equation of motion of three-dimensional vibration of the bridge when subjected to seismic excitations at all supports can be written as, Gimsing (4):

$$M\ddot{V}_t + M\ddot{V}_g + C\dot{V}_t + C_g\dot{V}_g + KV_t + K_gV_g = 0 \tag{3}$$

where M, C, and K = the mass, damping, and tangent stiffness matrices of non-active degrees of freedom of the bridge; M_g, C_g, and K_g = the mass, damping, and tangent stiffness matrices of the active degrees of freedom of the bridge (corresponding to the point of ground motion applications, supports); V_t =total nodal displacement; and V_g = displacement resulting directly from the support motions. Equation (3) can be written in a partition form as, Zhang, and et al. (6):

$$\begin{bmatrix} M_{bb} & M_{bg} \\ M_{gb} & M_{gg} \end{bmatrix} \begin{Bmatrix} \ddot{V}_b \\ \ddot{V}_g \end{Bmatrix} + \begin{bmatrix} C_{bb} & C_{bg} \\ C_{gb} & C_{gg} \end{bmatrix} \begin{Bmatrix} \dot{V}_b \\ \dot{V}_g \end{Bmatrix} + \begin{bmatrix} K_{bb} & K_{bg} \\ K_{gb} & K_{gg} \end{bmatrix} \begin{Bmatrix} V_b \\ V_g \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \tag{4}$$

Where, the subscript g= the degrees of freedom corresponding to the points of application (active) and directions of ground motion; and the subscript b= all other structural degrees of freedom of the bridge. Thus, the matrices M_{bg}, C_{bg}, and K_{bg} = rectangular mass, damping, and stiffness matrices, respectively, which represent the coupling between the structure nodes not connected to the ground (non-active) and the support displacements due to ground motion. The total nodal displacement may be decomposed into quasi-static displacement and vibrational displacement. The solution of equation (4) can be written as:

$$\begin{Bmatrix} V_b \\ V_g \end{Bmatrix} = \sum_{i=1}^{l} \begin{Bmatrix} S_{bi} \\ \delta_{gi} \end{Bmatrix} f_i(t) + \sum_{n=1}^{p} \begin{Bmatrix} \phi_n \\ 0 \end{Bmatrix} q_n(t) \tag{5}$$

Where S_{bi} = the ith quasi-static function that results from unit displacement in the ith degree of freedom at the supporting point; $f_i(t)$, $i=1,2,\ldots, l$ = the input displacement ground motions to the supporting points of the bridge in the three orthogonal directions; δ_{gi} = vector of which the ith element is equal to unity, with all its other elements being zero; $\{\phi_n\}$ = the nth free vibration mode shape of the bridge with all support-point displacement constrained; $q_n(t)$ = the nth generalized coordinate; and p = the number of mode shapes used in the modal analysis.

Dynamic Characteristics of the Free Vibration of the Bridge

Figure 2 shows a schematic representation for the static deflections due to the bridges own-weight and prestressing forces. The maximum static deflections for the deck at the center of the main span were found to be; 1) 1.75 m. for Suez-canal bridge, 2) 0.49 m. for Aswan Bridge. These results are expected since the main span for the Suez-canal bridge is almost twice that one for Aswan Bridge.

Unlike the classical suspension bridges, vibrations of cable-stayed bridges cannot be categorized as vertical, lateral, and longitudinal, Yay and Yang (7). The response of this type of bridges to earthquake excitations has special features due to the complicated interaction of the three-dimensional input motions with the whole structure, Brown john, and Xia (3), Zhang, and et al. (6). Figure 3 shows the lowest bridge's 5 mode shapes. Periods, frequencies, and mode shapes types are tabulated in Table 1. For Suez-canal Bridge, it is evident that a three-dimensional motion is associated with almost every mode of vibration. It should be noted that the first mode is a longitudinal horizontal mode along the bridge span. This is excepted since all supports are rubber-bearing type, which are weak in resisting horizontal forces except the end supports where they are of roller type. Where as for Aswan Bridge, mode shapes can be categorized into three types, towers-, deck-, and coupled-modes. Towers-modes (lowest mode shapes), which, have very low frequencies (long periods) are dominated by towers swaying in lateral direction (Y). The first mode is for the towers swaying in phase while the second one is for the towers swaying out-of-phase. The deck modes are dominated by the lateral sway in the horizontal plan. The third mode is close to half sin wave and the fourth one is antisymmetrical (one sin wave). The rest of the modes are coupled with vertical vibrations of the deck and torsional vibrations of the towers and deck.

From the aforementioned mode shapes it is clear that the bridge statical system has a dominant effect on the bridge vibrations. When tower and pier constitute one structural element, pylon, as in the case for the Suez-Canal Bridge it does not interact with the deck modes where as for case of Aswan Bridge the tower and deck are one element interacting together influencing the vibrations modes. Where roller supports exists, for the Suez-Canal Bridge, lowest mode shapes (dominant) are for the deck in the longitudinal direction. But for Aswan Bridge the dominant modes are for the lateral motion of the towers. Moreover, these modes are closely spaced in terms of frequencies. In addition, it should be mentioned that dominant periods of the Aswan Bridge are triple those of the Suez-Canal Bridge.

Dynamic Characteristics of the Seismic Induced Vibration of the Bridge

The Spectral accelerations for the mid-span vertical displacements due to earthquake for both bridges are shown in Figure 4. For the Suez-canal Bridge, the peak spectral acceleration occurs at periods 2.3, and 0.6 seconds, which are near the periods of the third and sixth modes of vibrations, respectively. In other word, peaks of spectral acceleration occur near the natural periods of the structure in which they already contain vertical motion. This is expected since the spectral acceleration is plotted for the vertical motion of the joint. Whereas for Aswan Bridge, The following response characteristics are evident from the Figure 1 there are a multi-modal contributions to each response quantity. These contributions are more pronounced in the high frequency (small-period) range of the response, 2) the high occurrence possibility of low frequency modes (long periods), in general, for any structure are for the first modes, 1,2,3,4. At these period ranges (3-13 seconds, beyond 5 sec. is not shown since it dies out)) the spectral accelerations have zero values. In other words, the bridge responses are far away from any resonance phenomena to occur. Generally, the wind forces have high frequencies. Accordingly, no threat to the tower stability is expected. Since the dominant mode shapes have low frequencies (long periods). Figure 5 shows the time-history responses for the vertical displacements for both bridges. It is evident that the Suez-canal Bridge has the highest responses. The aforementioned results, Spectral accelerations and time-history responses, are in agreement with the mode shapes.

CONCLUSIONS AND RECOMMENDATIONS

Several observations can be made from the results of the preceding analysis: 1) The deformation due to dead load must be considered in the seismic response analysis of long span cable-stayed bridges. 2) There is strong coupling in the three orthogonal directions within almost each mode of vibration. Therefore, a two-dimensional dynamic analysis is not adequate for this type of structures. 3) Generally, there is a higher mode contribution to the total responses. 4) The bridge statical system has a significant effect on the total bridge behavior. 5). As an alternative solution for Aswan Bridge, from structural point of view, the main span could have been 400m instead of 250, which is considered small compared to the existing concrete cable-stayed bridges (existing concrete bridges reached more than 400m for main span). This would have given clear navigation passage (Nile River width at the bridge site is about 400m) and have eliminated the cost of constructing the cofferdams for piers 7 and 8.

Although this study has predicted that the bridges are safe against wind forces, it is recommended to investigate the bridge characteristics under high wind speed. In addition, the use of stochastic methods for dynamic analysis (random vibrations) to predict the earthquake-response of such bridges is recommended. This can allow for studying the effects of support-excitation, cross-correlation, and modal cross-correlation on the bridges responses. The effect of soil-structure interaction, and local soil conditions at the site of the bridges on the dynamic characteristics and earthquake-responses of the bridges should be investigated.

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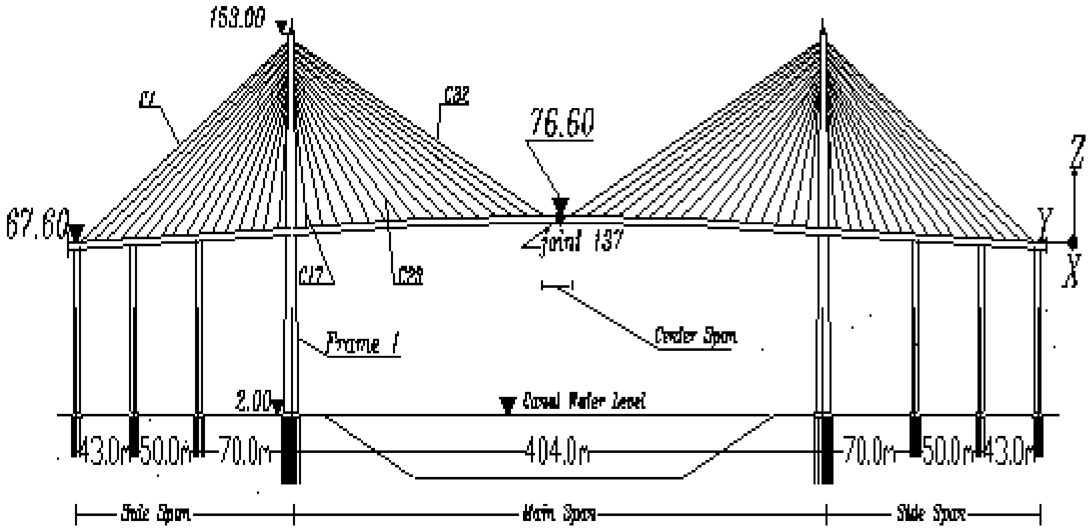
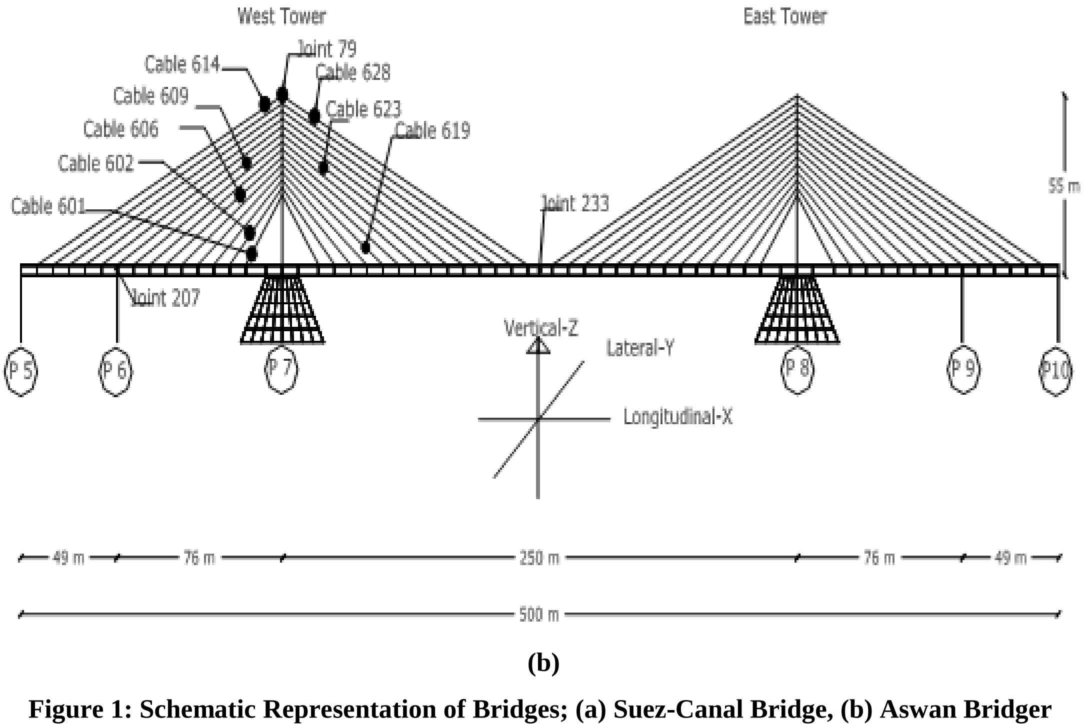
APPENDICES

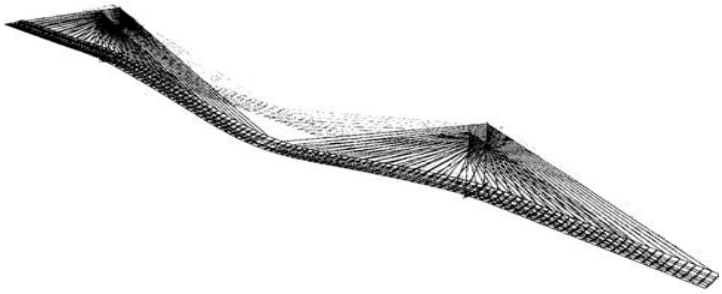


(a)

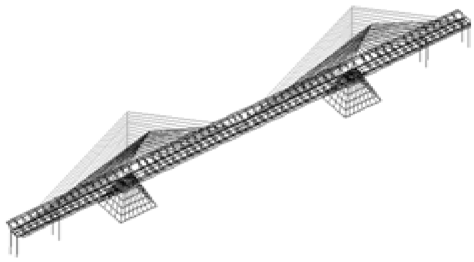


(b)

Figure 1: Schematic Representation of Bridges; (a) Suez-Canal Bridge, (b) Aswan Bridger



(a)



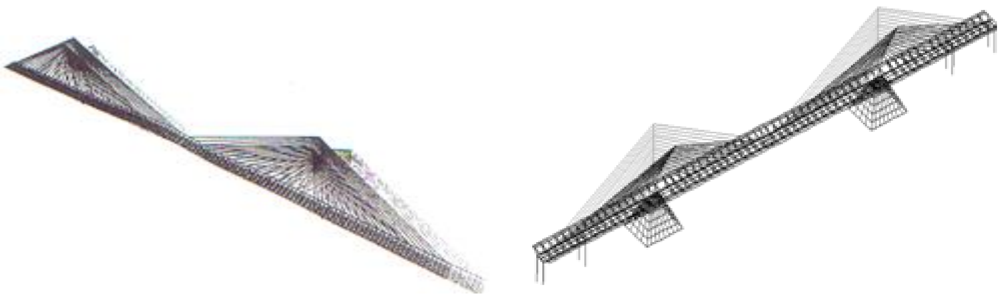
(b)

Figure 2: Static Deformation Due to Dead Load for; (a) Suez-Canal Bridge, (b) Aswan Bridge

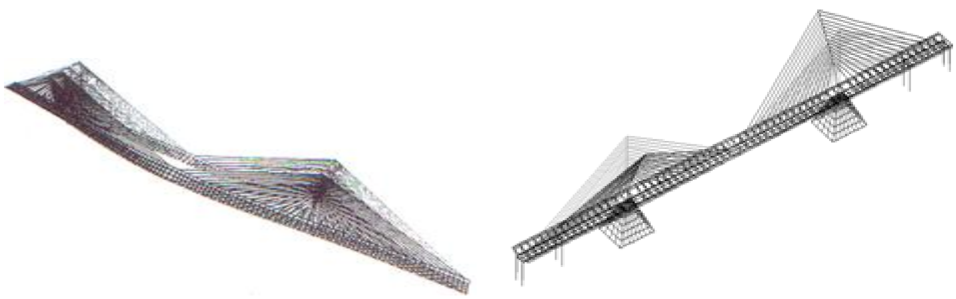
Table 1: Selected Mode Shapes

Mode	Suez-Canal Bridge		Nature of Mode Shape		Aswan Bridge		Nature of Mode Shape	
	Frequency (Hz)	Period (Sec.)	Pylon	Deck	Frequency (Hz)	Period (Sec.)	Tower	Deck
1	0.2568	3.8937	-----	L	0.076	13.064	LT	-----
2	0.2667	3.7499	-----	LT+ V	0.078	120693	LT	-----
3	0.4228	2.3605	-----	V	0.282	3.544	-----	LT
4	0.7507	1.0313	-----	V+LT+T	0.324	3.079	-----	LT
5	0.9696	1.0313	-----	L+V	0.537	1.862	LT	V+T

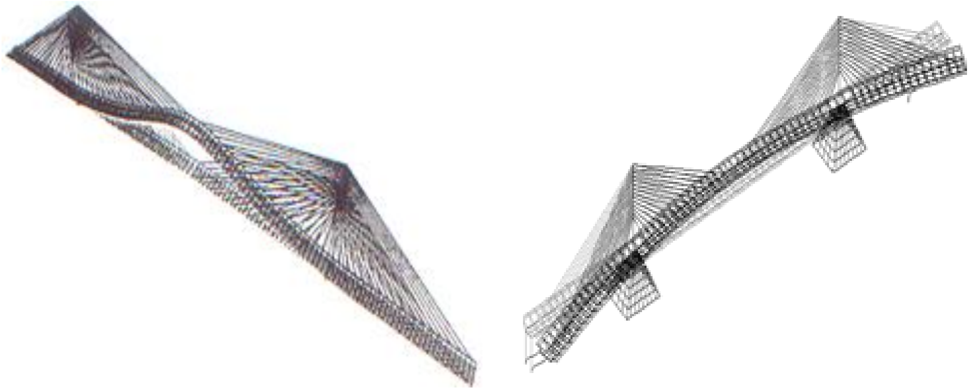
Where, V= Vertical, L = Longitudinal, LT = Lateral and T = Torsional



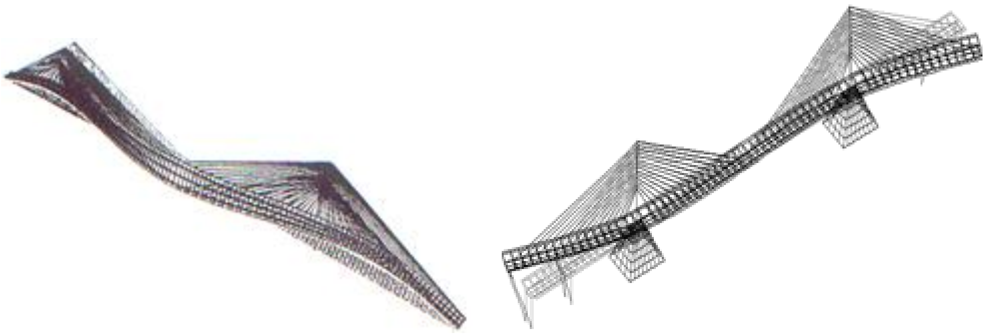
Mode 1



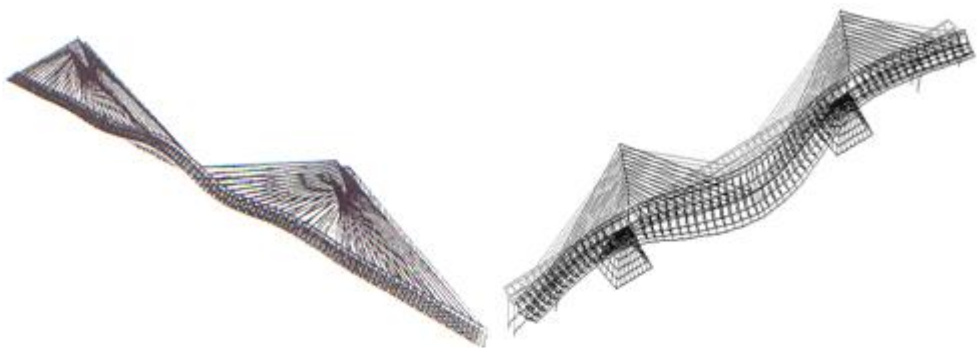
Mode 2



Mode 3



Mode 4



Mode 5

(a) **(b)**

Figure 3: Three Dimensional Mode Shapes; (a) Suez-Canal Bridge, (b) Aswan Bridge

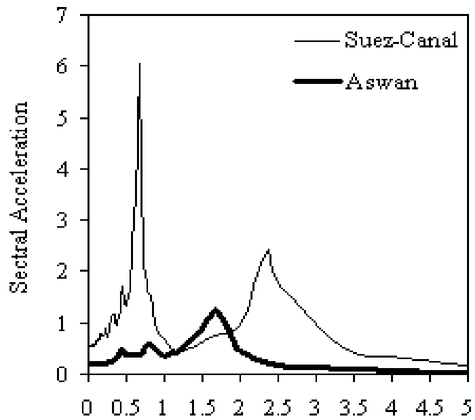


Figure 4: Spectral Acceleration for Vertical Displacement at Mid Span

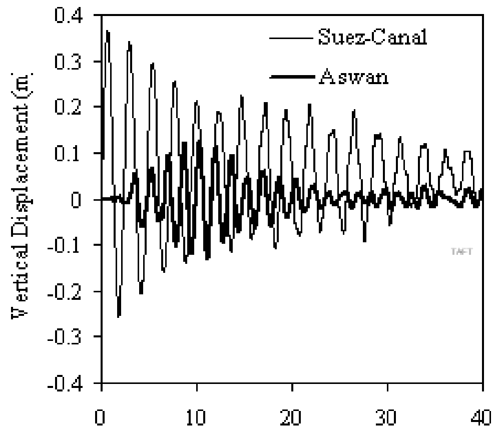


Figure 5: Time-History for Vertical Displacement at Mid Span